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Climate and Urban Morphology in the City of Barcelona: The Role of Vegetation

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.69125>

Abstract

Urban morphology defines many characteristics of a city, such as its urban quality, density, and free spaces layout with its vegetation, microclimate, and thermal comfort. All these variables have in common the element of urban space, which is where users develop themselves, making it an element of value. As the city evolves, environmental conditions of the area also change. One example is the urban heat island (UHI) effect. The UHI is defined as the accumulation of heat produced by the urban surfaces emitted to the environment, affecting the urban structure and the thermal comfort of users. As discomfort increases, urban public spaces lose their appeal and may be turned into deserted areas. One of the reasons is the lack of vegetation, particularly arboreal species, which protect these spaces from the solar incidence. In this regard, the questions arise as to how urban morphology affects the incidence of solar radiation in the urban canyon, and how vegetation and its characteristics influence climatic comfort. To develop these concepts, three introductory sections are addressed: the city of Barcelona, Barcelona climate, and urban morphology. Where the main variables are solar radiation, urban canyon, orientation, and the role that vegetation plays as a protection.

Keywords: Mediterranean urbanism, urban heat island, vegetation, outdoor thermal comfort, radiation

1. Introduction

Urban morphology defines many characteristics of a city, such as its viability, microclimate, vegetation and thermal comfort. All these variables have in common the element of urban

space, which is the space where users develop themselves, making it an element of value because it is the place where their travel and moments of leisure occur. As the city evolves, the characteristics change, leading to the birth of new variables, including the urban heat island (UHI). The UHI is defined as the accumulation of heat produced by urban surfaces emitting it to the environment, affecting the urban structure and the thermal comfort of users. This situation directly affects thermal comfort and recreation spaces.

Thermal comfort can be defined as the state in which a thermal balance exists. Thus, the definition of discomfort is the opposite state to this. Gradually, this urban thermal discomfort increases, turning urban areas that were previously widely used into deserted areas. One of the reasons is the lack of vegetation, particularly arboreal species, which protects these spaces from the solar incidence. For this purpose, one of the major interventions being implemented at the international level is the improvement of urban spaces, and the key element for this improvement is vegetation, since it provides great contributions in different climatic and urban aspects.

Questions arise as to how urban morphology affects the incidence of solar radiation in the urban canyon and how vegetation and its characteristics influence the microclimatic thermal comfort, with woodland being the main element of study, since it is one of the tools of greater dimension and use at the urban level. Previous studies [1–8] have validated that it is one of the greatest mitigating tools. The radiation, orientation and incidence in the urban canyon influence to a great extent how this urban space could behave that is why they are important variables of study [9–15].

To develop these concepts, four introductory sections will be developed: first, the Mediterranean, where concepts and data about the Mediterranean region and its cities will be developed; second, Barcelona city, which is the city of study; third, the climate of Barcelona and fourth, the urban morphology where the radiation and vegetation are dissected. The main variables will be solar radiation, urban canyon, orientation and the role played by vegetation as a protection and design tool, leading to relevant conclusions on the subject.

2. Methodology

The research methodology was based on analysis of the state of the technique of the urban morphology of Barcelona, which allowed evaluation of the main indicators. The method developed for this study combines energy simulations and *in situ* measurements of environmental conditions to evaluate the role of vegetation. Heliodon is a computer tool to evaluate and study the solar radiation over 3D urban models. It has been used to assess the impact of the urban canyon on the incidence of solar radiation in the streets of the city. Additionally, radiation and surface temperature measurements have been carried out. Through these simulations and measurements, calculations of the thermal comfort of these points of analysis were obtained to determine the quality of the space.

3. Mediterranean

A remarkable number of important cities converge in the Mediterranean region, such as Malaga, Valencia and Barcelona in Spain; Marseilles and Nice in France; Genoa, Rome, Naples and Bari in Italy; and Algiers, Oran and Tunisia in the south of the Mediterranean. Each of these cities has a different location in relation to the climate, soil and vegetation, as well as a different history and urban development. All these are relevant variables for the evaluation of a city. The climate and urban morphology will be the indicators developed in the climate and urban morphology.

Climate can be defined as the statistical description of the characteristics of the state of time over a period of a few months to millions of years [16]. The Mediterranean climate is characterised by temperate and rainy winters, autumns with torrential rains, rainy and temperate springs, and very hot and dry summers. Mean maximum temperature variations in different cities have been recorded during the period 1971–2000. The mean maximum temperature ranges reached 35°C in the city of Seville [16].

These climatic conditions depend on the location of the city and its urban conditions. For example, there are cities like Barcelona and Tarragona with a mean maximum temperature of up to 28°C in summer and a mean minimum temperature as low as 4°C in winter. Cities like Madrid record mean maximum temperatures of up to 31°C in summer and mean minimum temperatures as low as 2.6°C in winter. Cities such as Rome and Naples record mean maximum temperatures of up to 30°C in summer and mean minimum temperatures as low as 4°C in winter [16, 17]. However, cities such as Seville register mean maximum temperatures of up to 35°C in summer, being the highest in comparison to the previously mentioned cities, and mean minimum temperatures as low as 5°C in winter [16].

3.1. Vegetation

Vegetation is a living element that varies according to the conditions of a given environment. Studies have been conducted on how the minimum temperatures affect the frost resistance of a species [18, 19]. Species were classified in 10 zones of application of the vegetation according to resistance to these frosts (**Table 1**).

Classifications were performed to determine how the climatic zone influences the resistance of tree species. In this study, the areas of Valencia, Malaga, Alicante, Bari and Naples are classified as zone 10; the cities of Barcelona, Nice, Genoa and Rome belong to area 9. More inland cities like Madrid or Florence would be area 8.

It can be seen that these cities, due to their climatic conditions, have species resistant to medium frosts or, in the case of cities like Barcelona, not resistant to frost, indicating that climate is a factor that influences the contributions of a species in the urban environment. For this reason, when selecting a species for urban use, the climatic conditions and resistance of the tree species to this environment should be considered.

Zone	Resistance	
1–7	Hf	Strong frost resistance
8	Hm	Medium frost resistance
9	Hd	Resistance to weak frost
10	H	Not frost resistant
T	E	Not resistant to cooling

Table 1. Classifications of tree species according to frost resistance.

3.2. Radiation

Solar radiation is an essential element for the development of any kind of life on the planet [9–15]. It is both a factor and a climatic macro feature in which the direction of the incidence of radiation depends on the relative movements of the Earth and the Sun [20].

The type of radiation received from the Sun is distributed over a wide area of the electro-magnetic spectrum. It is preferably in three types: short-wave (ultraviolet) radiation, visible radiations and long-wave (infrared) radiation. This set of radiation affects the outer limits of the Earth’s atmosphere with an approximate irradiation value of 1400 W/m², which is called the solar constant [9–15, 20].

The cities mentioned above have different levels of incidence as far as solar radiation is concerned. The city of Seville, in the Autonomous Community of Andalusia in Spain, has the highest levels of average global irradiance, reaching 8.10 kWh/m² a day during July, although cities such as Malaga, Valencia and Barcelona have values very close to Seville, being maintained during the summer months in limits of 6.12–8.10 kWh/m² a day [21]. Cities like Genoa, Rome, Bari and Naples, to mention other cities of the Mediterranean, display lower values (although not low) of global irradiance compared to those reached in the cities of Spain, staying in a range from 5.22 to 6.86 kWh/m² a day during the same summer months (June, July and August) [22].

The study of the incidence of solar radiation in cities is of great importance in observing these values, since it is one of the parameters with the greatest impact on urban thermal comfort. The city of Barcelona presents an urban morphology in which the Eixample, a product of the Cerdà Plan [20], and its location and climatological conditions, is a case study of great interest in the subject to be developed in this chapter.

4. Barcelona: city

Barcelona is a large co-capital city of Spain like Madrid, belonging to the autonomous community of Catalonia. It is located on the shores of the Mediterranean Sea with the mountain chain of the Pyrenees and it is 160 km from France. The city is bounded on the north by the

river Besos, to the south by the river Llobregat, to the east by the Mediterranean Sea and to the west by the Collserola mountain range.

Barcelona is a city with unique characteristics. This is due to its history and its transformation at both urban and economic levels, making it a city that values users, urban space and vegetation, resulting in an urban model that has come to be called the Barcelona model of urbanism. The climate, natural elements, orography, Collserola, rivers Besos and Llobregat, along with historical elements such as the walls and fortresses of Montjuic and Ciutadella largely determined the morphology of the city until the nineteenth century and the beginning of the twentieth century, when the old municipalities of Gracia, Sants and Sarria, among others, were added, and the expansion of Cerda was chosen as a new hygienic-rational means of growth and connection with these municipalities.

At the same time, the present form of the city with its natural elements, buildings, parks, gardens, squares and streets notably influences its own microclimate. In the last 40 years, the city has invested in elements of infrastructure, reorganisation of streets leading to an increase of vegetation, remodelling of sidewalks and urban spaces and creation of spaces open to users like rivers and beaches, among other endeavours. This has generated a modernised city where the main elements are the user and his or her needs. Such modernisation and investment of resources to improve urban elements have given the city an added value in large part by the urban landscape perceived by the user, since the equipment and conditioning of the urban spaces create a state of comfort linked to well-being and quality of life.

5. Barcelona: Mediterranean climate

Barcelona, with a latitude of 41° North, has a Mediterranean climate. It is characterised by seasons marked with air temperature with an annual average of 16° and global radiation in the horizontal plane of 174 W/m^2 . The typical Mediterranean coastal climate consists of five types [18, 19]. The climate of the city of Barcelona is temperate, in which the average of the coldest month is less than 18°C and in summers 19°C , with defined dry seasons and humid periods during the year. Barcelona is part of the Mediterranean climate, registering an average temperature of 16.5°C and precipitation of 599 mm in October. This climate can be defined as dry and warm in summer and cool and humid in winter. It has moderate oscillation, thus creating sclerophyllous forests [18, 19]. These characteristics of marked stations become a challenge at both the level of design of buildings and the urban level, posing challenges to the designer to generate elements and tools necessary to create comfortable interior and exterior spaces.

6. Barcelona: urban morphology

Barcelona is a metropolis that comprises several distinctive urban tissues. The most recognisable is the Eixample, not only because of its urban design but also because of its remarkable

extension. This urban area is linked to urban spaces such as streets, squares and walks that make it a city that invites its users to coexist in it, giving life and value to these spaces.

To achieve this well-being, there are climatic variables involved in its design, including air temperature, relative humidity, solar radiation and wind speed and direction, which are linked to key elements that are part of the environment: vegetation and building. For this reason, we will discuss the main indicators that influence this urban morphology and the thermal comfort of the solar radiation and vegetation.

6.1. Solar radiation and urban morphology

Solar radiation is a key variable that modifies the thermal contributions to the environment. Thus, its analysis and behaviour play an important role. Knowing its behaviour, we can determine what improvements could be made to protect users living in this urban environment.

The indicators involved this section are latitude, street orientation, urban canyon morphology (street width and height of the building), sky view factor (SVF), and the percentage of radiation that affect. We will evaluate each characteristic and how it influences the urban morphology of Barcelona. By evaluating these indicators, we can obtain solutions to improve these contributions that the environment receives through solar radiation, with vegetation as a key element.

As previously mentioned, latitude is a factor that directly influences the amount of radiation received, and this will be greater as we approach the equator. This is due not only to the inclination with which the Sun's rays fall on the surface of the Earth but also to the amount of atmosphere they must pass through [11–13]. In order to determine the direction and inclination of the radiation at each moment, we must know the relative position of the Sun and of the plane in question. Abacuses and solar charts graphically indicate the solar height (**Figure 1**).

Another important factor to consider in the study of the incidence of solar radiation is the orientation, which directly affects the access of solar rays in both the horizontal plane and the vertical plane [11]. Arnfield [23] developed different models of urban canyons, taking into account the aspect ratio (H/W) of Oke (street design and urban canopy Layer climate [24]) with different orientations. He concluded that the orientation of a street affects to a greater extent the amount of solar energy that affects the vertical planes, whereas the relation of aspect ratio (H/W) (**Figure 2**) directly influences the amount of radiation incident on the horizontal plane [11–13, 15].

The aspect ratio of an urban canyon is the geometric proportion between the height of the buildings adjacent to the street (vertical planes) and the width of the road (horizontal plane). This proportion is directly related to the SVF (**Figure 3**).

The SVF is the percentage of sky seen from a point located on any surface. This depends on the inclination and orientation of the surface. An $SVF = 1$ means a visible sky in its entirety, unobstructed. An $SVF = 0$ denotes a sky completely obstructed by obstacles (**Figure 4**) [11].

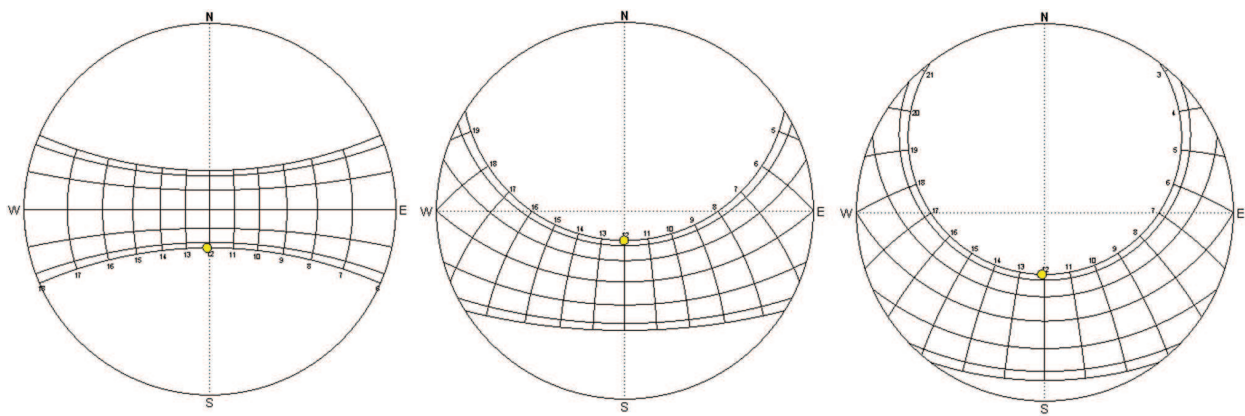


Figure 1. Stereographic solar charts, where one can observe the different solar trajectories throughout the day and the year. (Left and right): latitude 0°, latitude 41° N (Barcelona), latitude 51° N. Elaborated by the authors.

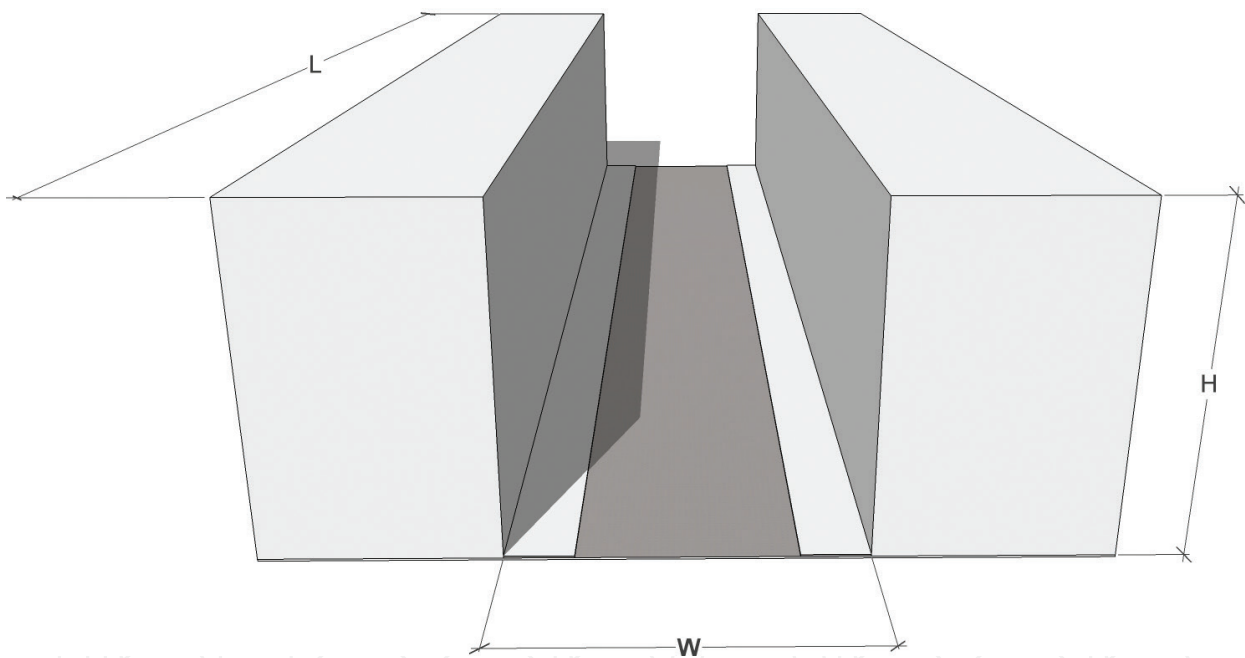


Figure 2. Urban canyons model, H/W aspect ratio. Elaborated by the authors.

The main climatic parameters that are affected by these two variants are the incidence of the solar radiation and the wind; however, as a consequence, the temperature and relative humidity are also affected [2].

The city of Barcelona, having a well-defined morphology (Eixample), exemplifies the energy performance of the urban canyon in terms of the incidence of radiation. Since it can be corrected through the proper use of vegetation, Avenida Diagonal, which crosses the Eixample district and is one of the main communication routes of the city, is taken as

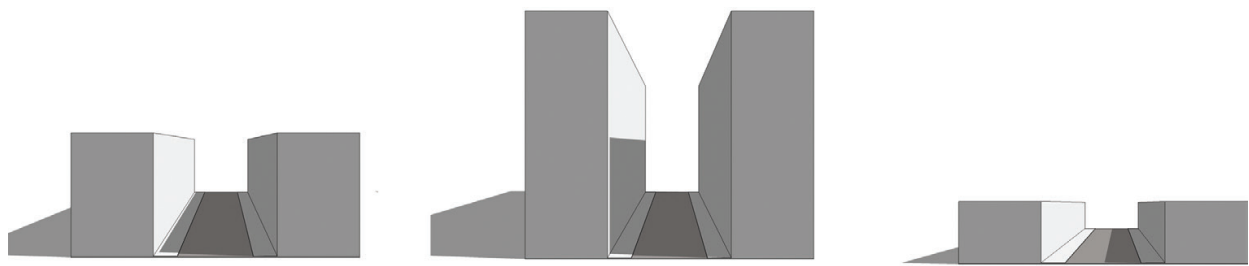


Figure 3. Schemes of different aspect ratios (H/W) of urban canyons (left and right): $H/W = 1$, $H/W = 2$ and $H/W = 0.5$. Elaborated by the authors.

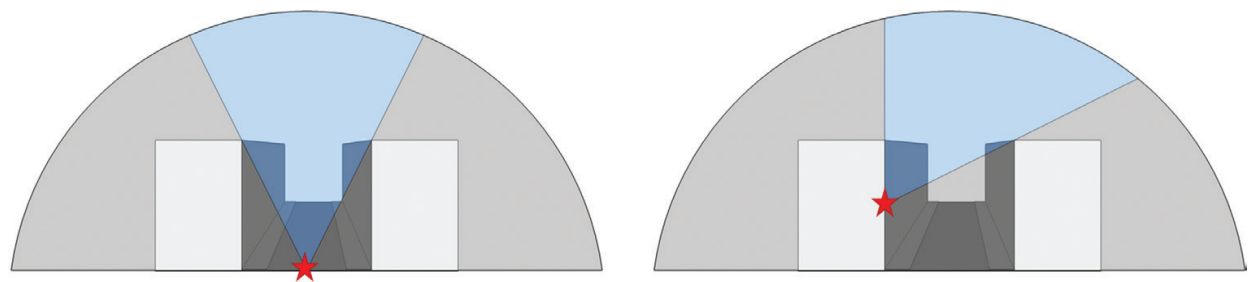


Figure 4. Schemes that show how the geometry and the plane of incidence affect the sky view factor. Elaborated by the authors.

a case study. It has a steady flow of pedestrians and vehicles and a continuous section of 50 m wide and about 10.5 km in length, with an orientation of WEST SOUTH WEST–EAST NORTH EAST (WSW - ENE).

For this study, Avenida Diagonal will be divided into two sections: the left section of the Ensanche (Esquerra de l'Eixample) would run from Plaza Macia to Passeig de Gracia and the right section of the Ensanche (Dreta de l'Eixample) would run from Passeig de Gracia to Passeig de Sant Joan. These sections differ mainly by the tree species they present and the height of their adjacent buildings.

The aspect ratio presented in the left section is 0.48 (24/50 m), while the right section is 0.42 (21/50 m). They are very similar, so urban vegetation will play a very important role in the amount of radiation incident on the horizontal plane, which presents notorious differences between the two cases. The left section presents species like the plane tree, canary palm tree and Mexican fan palm; the right section of the avenue presents trees like the hackberry tree, plane tree, holm oak and Judas tree (i.e. trees with denser foliage) (**Figure 5**).

The simulations and results of this case study were obtained using the software Heliodon2 [25] and were prepared for June 21 (i.e. at the beginning of summer), when temperatures are quite high. The right section has an SVF of 69.3% (placing the point at the centre of the street) and an aspect ratio of 0.42; the left section has an SVF of 62.1% and an aspect ratio of 0.48 [15].

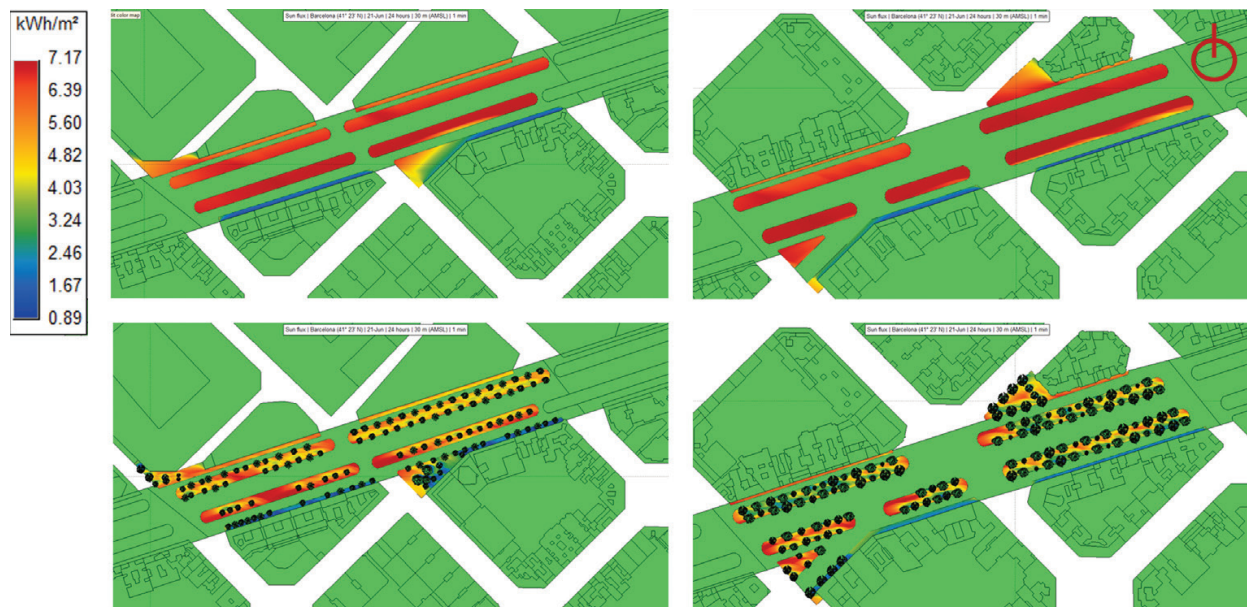


Figure 5. The images show the simulations of incident radiation in the left and right sections. Above: No vegetation is considered only the morphology. Below: Considering the existing vegetation. Authors' elaboration, software Heliodon2.

Simulations show that the presence or absence of urban vegetation in the street can make a significant difference (**Figure 5**). In the case of the right section, the percentage of reduction in the incidence of solar radiation ranges from 11 to 51%; in the left section, the percentages are lower, falling within a range of reduction between 9 and 38%. (This difference of reduction percentages between the two sections of Avenida Diagonal is due to the different tree species with which it is counted. Although the left section receives a smaller amount of solar radiation due to its greater aspect ratio and the right section has better energy performance thanks to the correct use of vegetation.) [15].

6.2. Vegetation and urban morphology

The vegetation is a living element that plays a role in the beautification and protection of the urban canyon. Three levels of green are defined: creepy plants, shrubs and woodland. These three elements are the indicators that offer improvement to the urban environment at the microclimatic and psychological levels.

The level of ground cover plants is the surface of the ground covered by grass or turf. The role of these creepy plants is embellishment in the horizontal plane of green areas. At the level of comfort, these green horizontal zones absorb the solar radiation obtaining less contribution radiant temperature to the environment, contrary to the behaviour of the urban surfaces.

The shrub is classified as medium level, depending on the type of pruning can take different forms. The role of shrubs at the level of landscaping can be trajectory, barrier protection, among others. At the level of thermal comfort, shrubs create projected shade on the surfaces surrounding them, reducing the solar radiation reaching these urban surfaces.

The level of woodland is the species with the largest dimension and the most used at the urban level. Trees are used for the beautification of urban areas. At the level of thermal comfort is the protection of facade and pavement surfaces from solar radiation, diminishing the horizontal and vertical thermal contributions to the environment.

In this section, we will evaluate the contributions of these levels of vegetation to the urban space. Studies have been conducted on the behaviour and contributions of this vegetation at the urban level in the city of Barcelona on urban roads such as Passeig de Sant Joan, Avenida Diagonal, Carrer Bailen and Carrer Londres. The data obtained showed the levels of contributions provided by the vegetation in these spaces.

Passeig de Sant Joan has been a well-known and popular walk in the city for many years. It has been the centre of urban use for the inhabitants and tourists of the city due to its direct connection to historical elements of Barcelona, such as the Arc de Triomphe, Parc de la Citadel, Sagrada Familia and the beginning of connection between the Turons and the mountain of Collserola. It also offers a great variety of urban recreation spaces. This walk consists of the three levels of pasture, shrub and woodland in linear and perimeter layout. On the way to Passeig de Sant Joan is a variety of species, including the hackberry, China tree, Judas tree, plane tree, lime of large leaves and Tipuana.

The methodology used involved *in situ* measurements of the environmental parameters, High DynamicRange (HDR) photographs and field evaluation in the summer season at three specific times during the day. These measurements were made in the summer in July 2013. The results showed that people often live longer in recreational spaces that are protected by the projected shade of trees and shrubs.

The measurements showed a decrease of up to 23.6°C of the contributions of radiant temperature to the environment, thanks to the shade projected by the shrub and tree species. On the other hand, the areas covered by grasses dissipated less radiation to the environment due to the natural process of photosynthesis. This provided more comfortable urban spaces for visiting and recreation due to the decrease in radiant temperature.

Studies implemented in Carrer Casanova and Carrer Londres, urban roads in the expansion of Barcelona with different orientations SOUTH-EAST (SE) and NORTH-EAST (NE) but with similarities in the typology of urban canyon and vegetation, have evaluated the behaviour of the solar radiation and the contributions of the radiation in this type of urban canyon.

The methodology implemented in this study involved *in situ* measurements of environmental parameters, simulations of the behaviour of solar radiation in the Heliodon programme, evaluation of the SVF of the streets and photographic survey of the tree species. The tree species studied in this case were *Platanus x hispanica* and *Celtis australis*. These measurements were made in summer at three specific times of day in the year 2015.

The results showed that Carrer Casanova has an SVF of 37.4% and Carrer Londres of 39.5%, determining that they are roads with a similar SVF. The hour of greatest solar incidence is

when you can appreciate the contributions of the tree species to the environment. Similarly, due to the magnitude of the urban canyon, there was the effect where the shadow of the buildings managed to reduce the solar incidence on the road.

For the species *Celtis australis* at 13:00 hours, Carrer Casanova managed to decrease 852 W/m², which is reflected in a decrease of 27.1°C of radiant temperature to the environment. However, in Carrer Londres it managed to decrease 907 W/m², which is reflected in a decrease in the radiant temperature of 11°C. For the species *Platanus x hispanica* at 13:00 hours, Carrer Casanova managed to decrease 852 W/m², which is reflected in a 19°C decrease in radiant temperature to the environment. However, in Carrer Londres it managed to decrease 853 W/m², which is reflected in a decrease in the radiant temperature of 23°C.

The results show that both species provide similar contributions but at different levels, with *Celtis australis* contributing the most. This is due to the density of leaves, with *Platanus x hispanica* having medium density and *Celtis australis* high density. In the same way, it can be seen how the orientation influences the level of incident solar radiation. This proves that the density of the foliage of a species as well as the orientation of the urban canyon greatly influence the behaviour of the contributions to the environment.

Allowing to check that knowing and valuing urban spaces and how this influences the variable of a person's energy balance that is the balance between the flow of heat input that brings the environment to the body and the output of it.

Previous studies [1–3] have created a formula to determine the role of vegetation in this parameter. The formula consists of several variables that intervene in the immediate environment to determine this exchange and the contribution of the tree species. The calculation is

$$B = M + Ra \pm Conv - E - Re \quad (1)$$

B = energy balance, M = metabolism, Ra = radiation absorbed, $Conv$ = convection, E = evaporation and Re = radiation of long wave emitted by the body.

Studies have developed a methodology to determine the foliage of an arboreal species and included in this calculation, allowing to know at a higher average the contributions that each species provides. The methodology implemented in this study involved *in situ* measurements of the environmental parameters in two cities of different climates, selection of different tree species for the study and realisation of infrared photographs and photographic shoots for evaluation of the foliage. This methodology has been applied to two types of climates in the Mediterranean (Barcelona, Spain) and warm, humid weather (Santo Domingo and Dominican Republic).

A number of arboreal species were evaluated, determining the foliage of the tree species of urban use. In order to determine the lushness, the measurements were made *in situ* in summer and winter in deciduous and perennial species to learn the contributions that the species

provide in their lack of foliage. After the data were obtained, calculations were made of the energy balance of a person exposed under the foliage of each tree species.

Technical data were obtained to determine the contributions that this species provided in the improvement of the thermal comfort in these urban spaces. After obtaining these results, we evaluated the behaviour of these urban spaces with the lack of these species. The results reflect the importance of the use of vegetation in urban spaces, since if these species did not have the state of thermal comfort of a person it would be stressful [26–32].

A difference of protection of the tree species could be observed in this study. The results on a typical summer day at 11:00 a.m. solar time differ by 7°C in the case of a light species and 8°C in the case of a medium and dense species (**Figure 6**). These values are reflected in the users in a state of heat in the case of light species and a state of comfort in the medium and dense species. In lack of these species although its foliage is different it is reflected in the users in a hot state (**Figures 6 and 7**).

This shows that no matter the type of foliage of the species at the urban level, their contributions will always be positive. That depending the climate the foliage in the urban design is important, since many factors can vary from the thermal comfort of the users. The same analyses were carried out in several tree species of Barcelona and Santo Domingo to determine in quantitative and qualitative ways, the contributions they can offer to the immediate environment and its users. Technical data sheets were compiled to gather the relevant information for urban design, architects or landscapers, providing a tool for the correct choice of species. The obtained results show how the variables of urban canyon and the typology of arboreal species include in the environmental conditions and in the users, turning them into variables of great relief in the design.

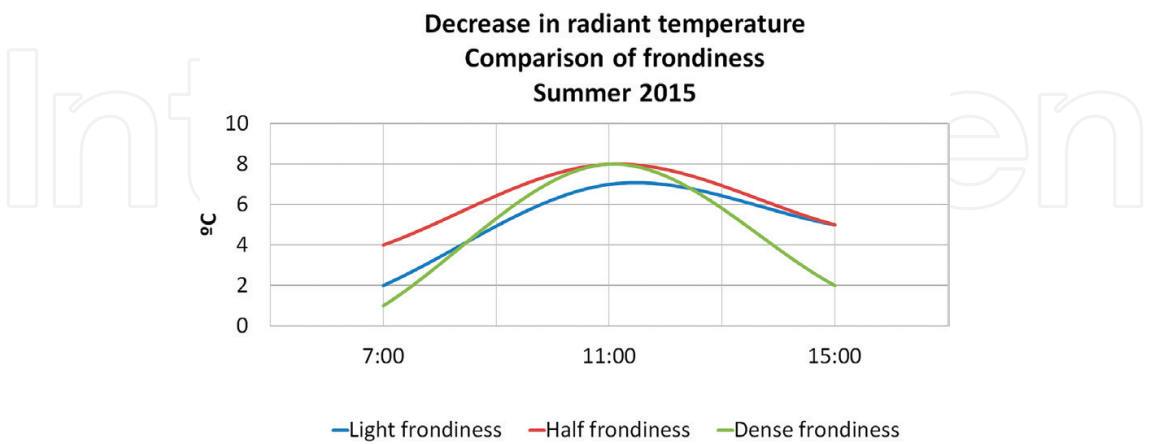


Figure 6. Comparison of frondiness of tree behaviour in radiant temperature.

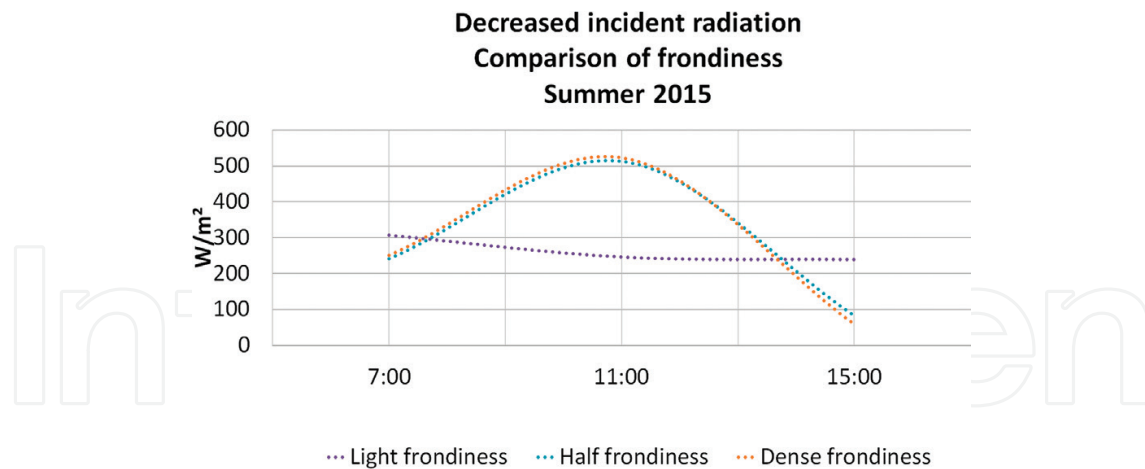


Figure 7. Comparison of frondiness of tree behaviour in incident radiation.

7. Conclusion

In this study, evaluations of incident solar radiation in Barcelona streets have shown which façades and time of year are more favourable or unfavourable. It is clear that the aspect with the greatest impact on the incidence or lack of incidence of solar radiation over the horizontal surface of the urban canyon is its morphology. As can be seen in Barcelona's Avenida Diagonal, this situation can be corrected by the right use of urban vegetation.

The typologies of vegetation of two cities were evaluated to learn their contributions in two different climates: a Mediterranean climate and a warm and humid climate. Vegetation is one of the best tools to improve the climatic conditions of urban spaces. Quantitative and qualitative results were obtained from the influence of vegetation on the thermal comfort of a person in the urban morphology, showing that vegetation is one of the most suitable tools for urban use.

According to the results, vegetation can be considered a useful tool to improve the climatic conditions of urban spaces, adding quality and value to the city. Evaluation of each tree species provides relevant knowledge about its environmental performance, which can be used in urban design as a tool of high value for designers.

Acknowledgements

The authors wish to thank the Ministry of Science and Technology Education of the Dominican Republic and its Minister Ligia Amada Melo; Dr Arq Helena Coch and her research team from the Department of Architecture, Energy and Environment; Msc Arq Curro Peña Ariza; Msc Arq Badia Masoud; Msc Arq Elena García and Lic Elayne Rojas.

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